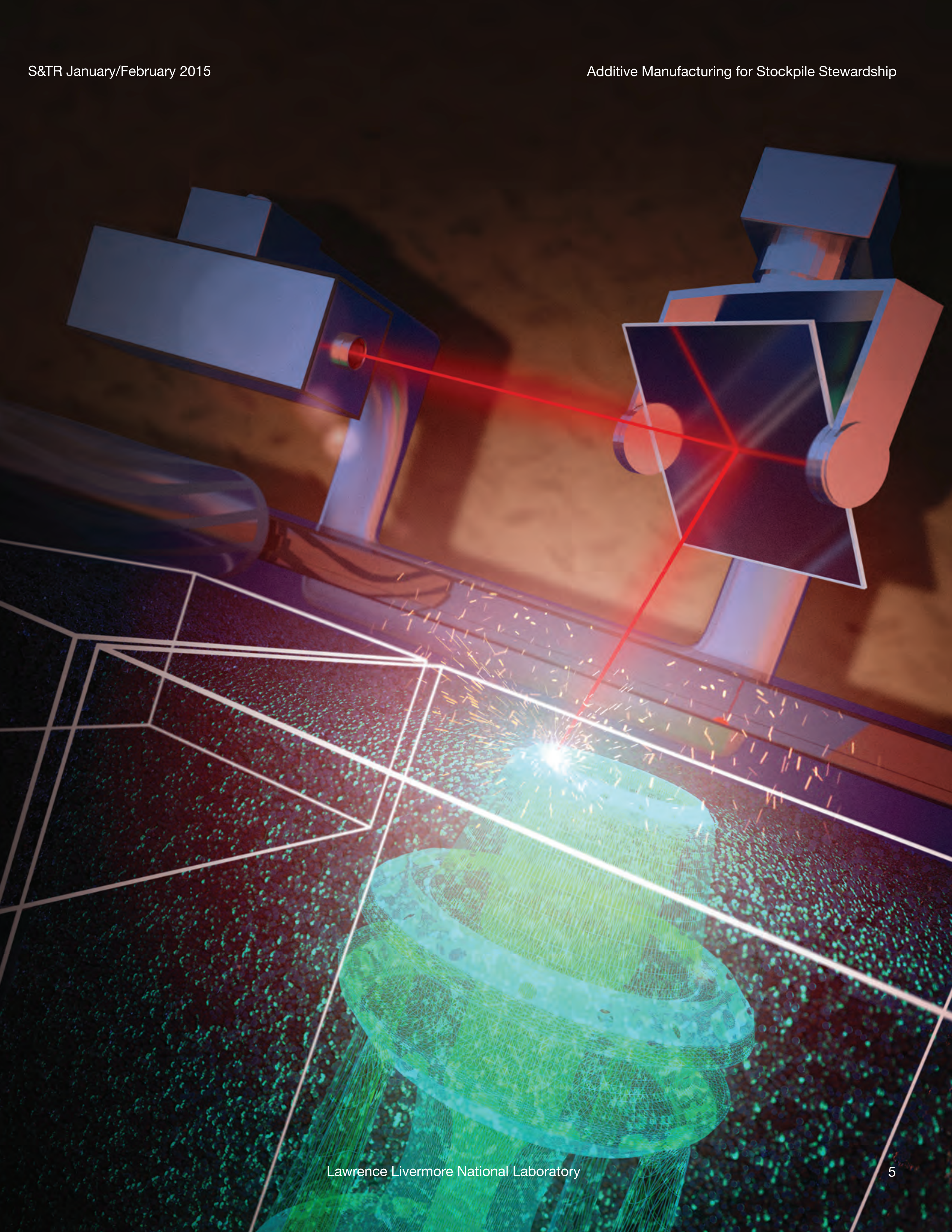
NEXT-GENERATION MANUFACTURING FOR THE STOCKPILE

Additive manufacturing may help transform the nuclear weapons enterprise.

WEAPONS refurbishment efforts called life-extension programs (LEPs) enable the National Nuclear Security Administration (NNSA) to maintain the nation's nuclear deterrent without resuming the production of new weapons or underground nuclear tests, both of which ceased roughly a quarter century ago. (See *S&TR*, March 2012, pp. 6–13; July/August 2010, pp. 4–11.) Sustaining the legacy manufacturing processes used for LEP component production is growing increasingly challenging for the NNSA laboratories and production facilities, which are tasked with keeping the aging weapons safe and operational. Many of the procedures are five decades old and geared toward mass production of weapons components. They entail lengthy multistep methods, expensive facilities, large lot sizes, and undesirable levels of hazardous waste generation. Some processes are no longer operationally feasible because of environmental issues, while others call for materials difficult to obtain.

Advanced manufacturing technologies such as additive manufacturing (AM), together with high-performance computing (HPC), could be used to develop next-generation manufacturing processes and materials for the NNSA complex. AM methods, in which layers of material are built up as prescribed in a digital file, can be used to quickly, easily, and precisely create objects with complex shapes. The superior material design and manufacturing process control available through AM can facilitate the creation of objects with more desirable material properties and performance than conventional subtractive manufacturing technologies. AM is already being exploited by a wide range of industries to drastically reduce product development and production time lines, particularly for low-volume specialty parts and tooling.

Recognizing that AM could greatly benefit national security missions, NNSA has launched a multiyear, multipronged initiative to explore, mature, and adapt the most promising commercial AM technologies and to develop new techniques. NNSA's success will rely on the manufacturing expertise of its production plants and the unique science-based stockpile stewardship capabilities of its laboratories. "For NNSA to realize additive manufacturing's important benefits in a reasonable time frame, it needs multidisciplinary labs such as Lawrence Livermore working closely with its production plants," says Melissa Marggraff, deputy principal associate director for Livermore's Weapons and Complex Integration Principal Directorate and coordinator for NNSA's many AM activities. "We have materials science, engineering, high-performance computing, and certification expertise that can help make this effort a success." Lawrence Livermore has five AM labs and more than 80 material scientists, chemists, physicists, engineers, and computational scientists developing advanced materials and manufacturing processes.



In collaboration with other NNSA laboratories and production plants, the Laboratory is studying and expanding the range of materials and component types amenable to AM. The collaboration is also exploiting the flexibility of AM processes to enhance the properties and performance of components. In addition, Livermore scientists are using HPC-based modeling and simulation to accelerate AM process qualification. NNSA's AM experts envision widespread use of the technology across the weapons complex, from manufacturing tooling and simple weapon replacement parts, such as cushions, to developing advanced materials, such as high explosives and nuclear components.

Livermore AM technician Manuel Iniguez holds a metal part produced in partnership with the Y-12 National Security Complex. This match drill fixture is the first additively manufactured part to be qualified for NNSA production and takes one-fifth the labor hours to produce as compared with previous manufacturing methods. (Photo by George Kitrinos.)

Tailoring Industry Processes

NNSA researchers have begun to strategically adopt existing AM capabilities and methods for stockpile-relevant applications and have already achieved some early successes. For instance, the Y-12 National Security Complex, with support from Livermore AM experts, has been exploring the feasibility of using industry-developed metal AM machines and processes to manufacture tools.

As part of this effort, Y-12's Derek Morin spent a year at Livermore, during which he worked with the Laboratory's AM experts and Y-12 end users to manufacture select metal tools. For several of these tools, the Livermore–Y-12 team fabricated both an AM replica of the wrought part and an enhanced version of the part. "We wanted to show how AM expands the design possibilities," says Livermore mechanical coordinator Steve Burke. "We no longer need to make a round hole when a square or oval hole will work better."

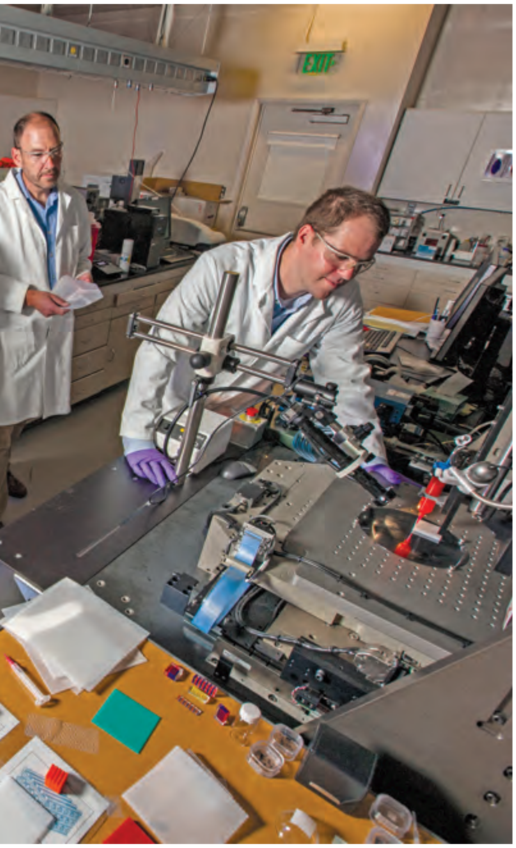
The ongoing collaboration has also demonstrated how AM can shrink production costs for intricate components such as gears by largely eliminating assembly and machining. A match drill fixture, the first piece of production-qualified tooling made by AM, has already entered use at Y-12. The new approach for producing this tool consolidates 5 parts into 1, thereby eliminating 12 welds and reducing waste.

Additive manufacturing (AM) researchers produce polymer parts using Livermore's direct-ink-writing machine. Shown here (left to right) are Chris Spadaccini, Tom Wilson, Robert Maxwell, and Eric Duoss. (Photo by George Kitrinos.)

NNSA sites estimate that 50 percent of its tools could be made using AM in five years. In which case, tooling production costs would be reduced 75 percent, development time 80 percent, and production time 60 percent, while potentially improving tool performance. Further, the items could be printed on demand, reducing inventory and freeing space.

Designing Special Properties

Livermore is engaged in challenging materials research in an effort to control and customize a weapon



With AM, scientists and engineers can control the properties and structure of a part in three dimensions. Livermore researchers have demonstrated they can create AM pads and cushions with different tensile or shear properties within the same component, an unprecedented achievement. (Photo by George Kitrinos.)

component's properties with AM. For one project, a team of engineers and materials scientists has developed a method for additively manufacturing cushions and pads that protect and position components within a nuclear weapon. (See *S&TR*, September 2014, pp. 20–23.) Traditionally, cushions and pads have been made of foam through a manufacturing process that does not allow for complete control of the shape, size, and distribution of air pockets. Consequently, the performance of the material cannot be precisely predicted.

Using a silicon-based "ink" that cures into a rubbery material, the team has designed and fabricated pads and cushions with direct ink writing (DIW). (See *S&TR,* March 2012, pp. 14–20.) DIW machines deposit ink on a substrate one layer at a time, in a predetermined pattern. The resulting structure is then cured with heat or ultraviolet light. With this technique, the team can better control the material's mechanical and directional properties than when working with foam. Engineer Chris Spadaccini says, "By controlling the architecture of a microstructure, we can create materials with previously unobtainable properties in the bulk form."

The team can also create novel combinations of properties, such as a pad that is easily compressible at one end and stiff at the other. The new method increases production uniformity and allows researchers to better model the materials and their performance. Moreover, DIW-produced polymer cushions are 85 percent cheaper than foams manufactured with legacy approaches and can be made in a tenth of the time. DIW pads will likely be among the first additively manufactured components incorporated in an LEP. Livermore researchers are working with manufacturing experts at the Kansas City National Security Campus to establish the AM production infrastructure, refine processes, and produce qualified parts.

Livermore researchers are also optimizing the structure of metal components using AM. Mechanical engineer Howard Rathbun develops strong yet lightweight lattice structures on a scale too fine for conventional metal manufacturing techniques. "We want to take advantage of the strength and stiffness of lattice structures to help resolve some stockpile stewardship technical challenges," says Rathbun."

To achieve a stronger, stiffer structure, each lattice is configured so that none of its struts can bend. Standard design tools could not create lattice structures of the desired complexity, with thousands or millions of individual millimeter-high struts, so Rathbun's team developed computational design tools that run on Livermore's supercomputers. Using these tools, the researchers can create lattices that conform to a curved surface while retaining superior lattice performance. "HPC is a significant aspect of developing metal lattice structures and ensuring we have confidence that they will meet performance requirements," says Rathbun.

These standards can be demanding. For instance, one stretch-dominated lattice structure can absorb very high loads and spring back without exhibiting permanent deformation. Metal lattices can be designed to serve multiple simultaneous roles, too. For example, the open spaces within a lattice can be used to pass fluid, allowing the lattice to function as both a heat exchanger and a load-bearing structure. The Laboratory is also exploring other paths for maximizing the mechanical properties of lattice and multimaterial components while minimizing weight, with the aid of sophisticated tools. For instance, Daniel Tortorelli of the University of Illinois at Urbana–Champaign has been working with Spadaccini's team to use computational modeling methods known as topology optimization to create designs for AM fabrication.

Printing Exotic Materials

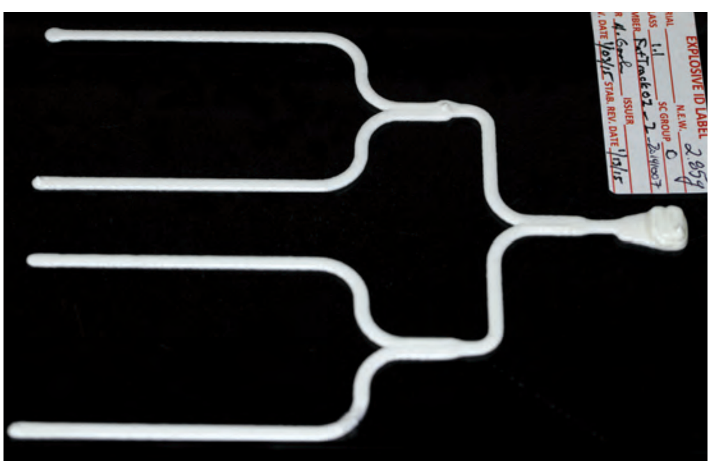
An effort to print exotic materials, such as explosives, has necessitated the development of new AM methods as well as the adaptation of some commercial technologies. Using AM methods, Laboratory scientists aim to improve a manufacturing process and product that have remained essentially the same for the past 65 years. Materials chemist Alex Gash observes, "AM provides an opportunity to gain more control over the sensitivity, safety, and performance of the explosive."

A high explosive's crystal structure is pocked with defects, or pores. When the explosive is shocked, these pores both collapse and heat, initiating the explosion. "We know that explosive performance and safety are affected by defects in the material," Gash adds. "These defects exist at the mesoscale, from about 1 to 100 micrometers. AM gives us the potential to manipulate structures on that scale, unlike conventional manufacturing." Controlling the distribution of the pores should yield a safer and more predictable explosion. For instance, the team could design parts with a density gradient, which might enable reliable initiation.

For its feasibility experiments, the team targets small components, such as the boosters that set off the main high-explosive charge of a nuclear device. Detonators and boosters are more practical to print than larger components at this stage. Thus far, Livermore researchers have demonstrated, using mock energetic materials, that they can manipulate material microstructures at critical length scales for controlling the response and performance of explosives. Printing of actual high explosives began in September 2014 in a specially constructed laboratory for remotely operating AM techniques at Livermore's High Explosives Applications Facility. Preliminary printing and test results are encouraging.

Livermore researchers are also developing new techniques for manufacturing other components, including materials associated with dispersion-type nuclear fuels. Initial efforts focus on using selective laser-melting (SLM) technology to produce parts from a uranium–niobium alloy that are high strength as well as oxidation resistant. The SLM powder-bed AM technique uses intense laser energy to fuse fine metal particles and produce a three-dimensional (3D) part. To enable this and other AM research, a multidisciplinary team set up a laboratory and SLM machine specifically for working with reactive and radioactive powders, a significant effort. "It was challenging to determine the potential hazards and to develop creative ways for implementing the required controls," observes Paul Alexander, lead SLM machine operator. "However, with a diverse team of experts, we were able to establish a research and development facility that is well prepared for these unique challenges."

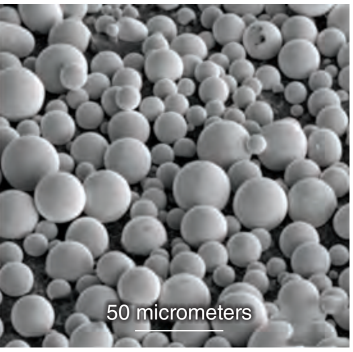
In May 2014, the facility became operational, and the uranium–niobium alloy was printed for the first time using a commercial SLM machine. The team is now proceeding to characterize the SLM-produced test objects. Compositional studies using various microscopy techniques have helped the research team understand how uranium and niobium atoms are distributed during printing, how particle size affects printing results, how laser settings determine the material's porosity, and how impurities affect the material's properties.

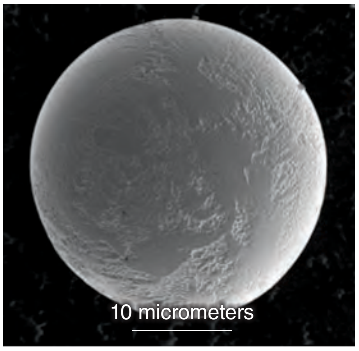


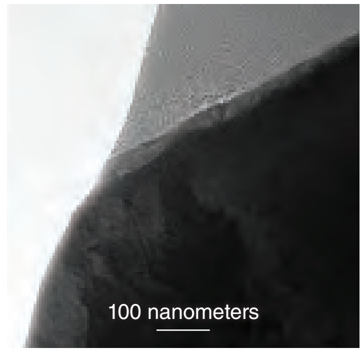
An object made using an extrudable explosive demonstrates Livermore's ability to additively manufacture conventional high explosives.

Intensive Characterization

The success of ongoing AM research relies on the ability of researchers to understand and control the properties and performance of additively manufactured materials in order to ensure qualification of AM components. AM entails not only a new production process but also potentially different component materials. Chemist Larry Fried explains, "Even if we begin







Material scientists Geoffrey Campbell, Luke Hsiung, and Joseph McKeown have characterized the surface oxide layer and microstructure of uranium–niobium powder using (left and center) scanning electron microscopy and (right) transmission electron microscopy. This information contributes to understanding how factors such as size distribution and quality of the particles affect the AM process.

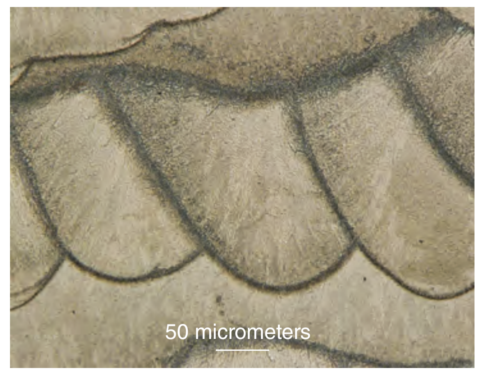
with the same metal, the AM process changes the metal's microstructure."

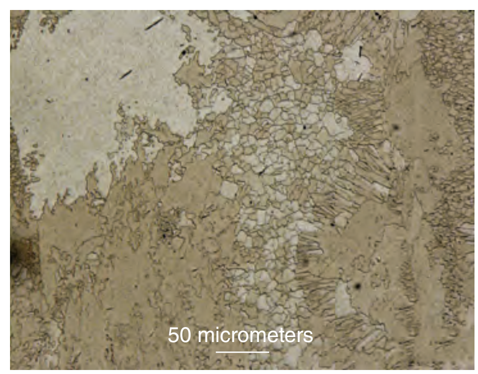
AM-produced metals can exhibit structures, properties, and performance that differ from their cast and wrought counterparts. This issue continues to dominate concerns with exploiting AM for commercial applications. For example, any pores and pockets of unmelted powder that form during the SLM powder-bed process will affect the metal's density. Furthermore, the rapid melting and solidification that SLM and other metal AM techniques impose on the material can change the distribution of crystal orientations within the resulting product. A significant amount of industrial and academic research and development is directed at determining the effects of these differences on a wide range of material properties.

"AM methods generally produce metal structures with more impurities and finer grain sizes, both of which make them stronger," says materials scientist Geoffrey Campbell. "Trade-offs exist, of course. More strength usually means less ductility, and ductility is what allows many metals to bend and deform without catastrophic failure." Significant future research and development will be directed toward understanding and exploiting these trade-offs.

Livermore researchers subject AM-produced metals to the full range of characterization methods in a materials scientist's toolkit, such as computed tomography, electron microscopy, x-ray diffraction, and ultrasonic sensing, as well as some less common tools. At the nanosecond and nanometer scale, they use the dynamic transmission electron microscope (see *S&TR*, September 2013, pp. 4–11) to study how metals solidify under laser-melting conditions. To characterize residual stresses within AM parts, they have collaborated with colleagues at Los Alamos National Laboratory to perform neutron diffraction studies. Optical metallography provides them with information on impurities in the microstructure. Other experiments performed include simple comparisons of weight and density, chemical analyses, and tests for characteristics such as strength and elasticity.

Experiments at other Department of Energy facilities complement Lawrence Livermore's examination techniques. Materials scientist Amanda Wu is collaborating with scientists from Los Alamos, Argonne, and Brookhaven national laboratories to examine the effects of AM on the fine-scale crystallographic structure of uranium–niobium, using Argonne's Advanced Photon Source. Materials scientist Holly Barth is conducting in situ mechanical testing of AM materials using synchrotron radiation microtomography at the Advanced Light Source at Lawrence Berkeley National Laboratory.





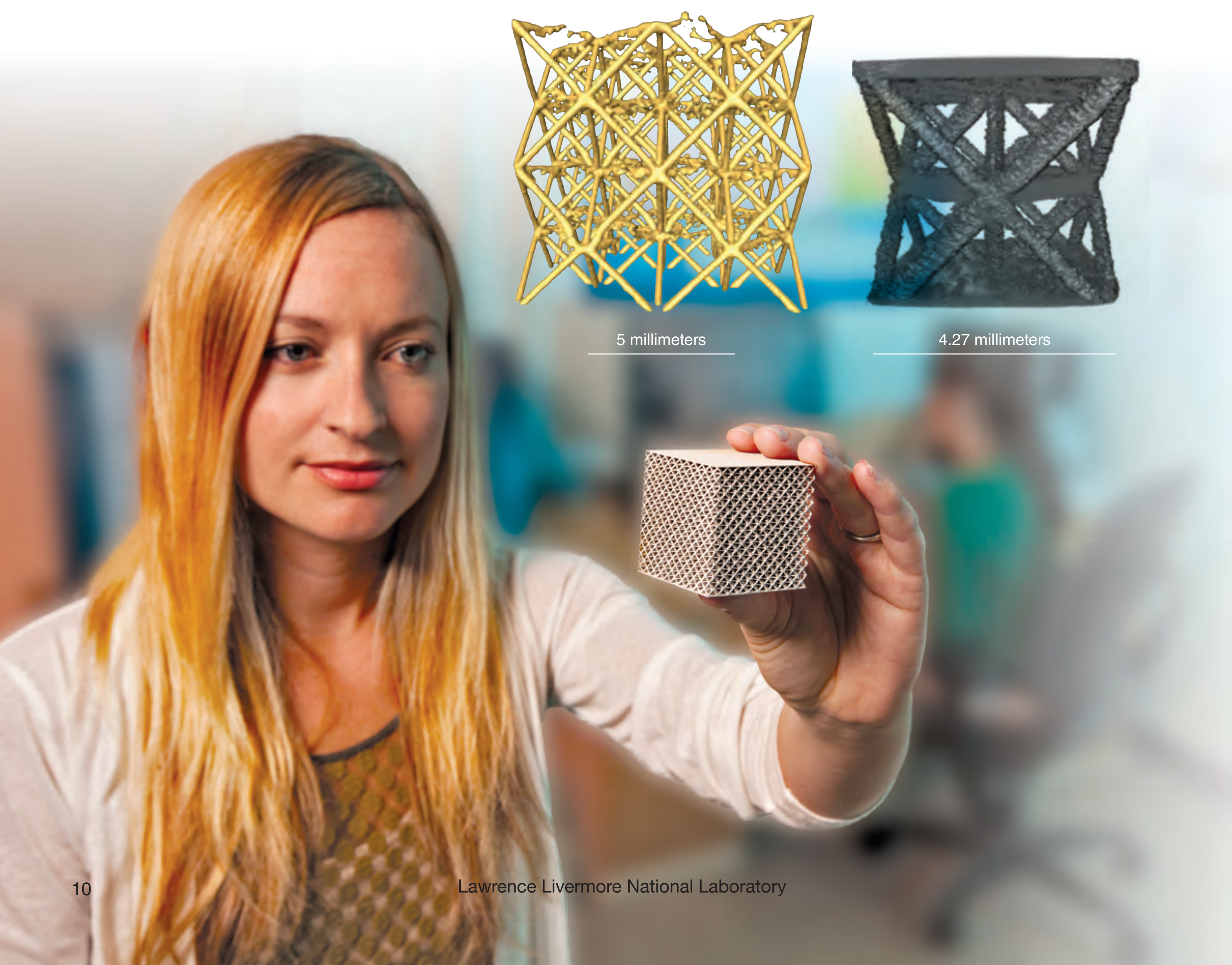
Characterization has revealed that with common postprocessing methods such as heat treatment, AM metal samples can achieve similar microstructures to those of conventionally manufactured metals. Optical micrographs created by Amanda Wu depict (top) an additively manufactured uranium–niobium sample without postprocessing and (bottom) a sample that has been radically transformed through solution annealing. The transformed microstructure resembles that of samples produced by other methods.

(below left) Materials scientist Holly Barth holds an additively manufactured metal lattice structure. A combination of modeling and synchrotron radiation microtomography experiments helped identify and correct some initial printing problems compromising structural integrity. (below center) This tomographic three-dimensional (3D) rendering of a stainless-steel lattice structure shows higher-than-desired porosity and disconnected struts, while (below right) the other tomographic 3D rendering shows a titanium alloy lattice structure with acceptable density and strut connectivity. (Photo by George Kitrinos.)

Barth's goal is to relate mechanical properties to microstructural observations in SLM-produced titanium alloys and stainless-steel samples. Her experiments generate micrometer-scale 3D images of samples as they are compressed or stretched. These images are used to track the damage evolution of potentially performance-limiting features such as misprinted lattice struts, large pores, or uneven pore distributions. For one study, Barth compared wrought stainless steel with AM stainless steel of two densities and found the AM metals that had been heat-treated to achieve the desired microstructure displayed similar properties to wrought metals, up to a certain threshold of porosity. At times, the build "errors" accumulate beyond acceptable ranges. Livermore computational efforts are attempting to quantify these ranges.

More Testing Ahead

Livermore researchers will soon begin more extensive laboratory testing of AM parts to assess their dynamic behavior. Experimentalists will use a combination of techniques, including laser-driven shocks, dynamic compression, conventional gas-gun tests, and explosives compression. Using laser-driven ultrafast shock experiments, Fried's group will study the material response of AM plastics on



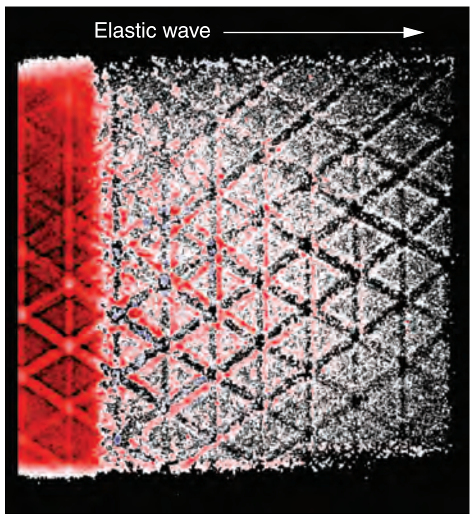
scales of hundreds of picoseconds and micrometers. This technique complements standard gas-gun tests, which interrogate material behavior on scales of centimeters and microseconds.

Materials scientist Mukul Kumar's team has begun conducting gas-gun experiments on plastic and metal AM samples at the dynamic compression sector of the Advanced Photon Source. This facility enables time-resolved x-ray diffraction and imaging measurements during compression experiments with spatial resolutions of about 10 micrometers. The technique will help researchers understand how metal lattices respond to shock waves similar to what would occur during weapon operation. Ultimately, the deeper understanding of AM materials gained through ongoing characterization and testing activities will inform the development both of AM stockpile components and of accelerated approaches for certifying AM parts. (See the article beginning on p. 12.)

National Security Applications

Livermore researchers and their NNSA partners are demonstrating how strategic use of AM can speed the development and enhance the quality of metal and polymer replacement weapon parts, prototypes, test objects, and related materials for stockpile stewardship activities. In time, AM could fundamentally change the way the nuclear weapons complex produces parts by shrinking the manufacturing production footprint, revitalizing the stockpile infrastructure, and helping bring about a leaner, more sustainable, and more agile nuclear enterprise. As a side benefit, AM's challenging multidisciplinary science and compelling mission may also help attract and retain the next generation of stockpile stewards at laboratories such as Lawrence Livermore.

"As we develop the core capabilities with NNSA, we will also support the development of national security capabilities more broadly," says Marggraff. For example, AM can be used to enhance capabilities to disarm nuclear weapons, train nuclear emergency responders, and gain insights regarding high-explosives performance and new conventional weapons concepts. Further, it can help intelligence experts understand how new manufacturing technologies could be exploited by other nations or entities to produce weapons that are otherwise difficult to make or that do not currently exist.



Dynamic compression experiments at Argonne National Laboratory's Advanced Photon Source performed by Livermore materials scientist Mukul Kumar and his team are providing insights into the physics associated with the deformation of AM metal and polymer lattices, including the propagation of traveling waves and their interaction with the material's microstructure.

Because the payoffs for the AM initiative won't be realized for at least a few years, maintaining the necessary momentum for the project demands dedication and passion from the researchers. "Our 'secret weapon' at Livermore is our enthusiastic and engaged management and staff," observes Rathbun. "We are excited about additive manufacturing's possibilities, and together we have the experience and abilities to make it happen."

—Rose Hansen

Key Words: additive manufacturing (AM), direct ink writing (DIW), foam, high-density part, high explosives, High Explosives Applications Facility, high-performance computing (HPC), life-extension program (LEP), National Nuclear Security Administration (NNSA), nuclear stockpile, nuclear weapon, pore, selective laser melting (SLM), uranium.

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